



Coupling study of a novel thermocompressor driven pulse tube refrigerator



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HIGHLIGHTS

- We present a novel thermocompressor driven pulse tube refrigerator.
- We propose the impedance matching method for the coupling work of the refrigerator.
- Three different pulse tube refrigerators were tested to verify our method.
- We report the lowest no-load temperature of 70.4 K for this type of refrigerator.

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ABSTRACT

The impedance match is important for the efficiency and available acoustic power of thermocompressor (TCP). The filling pressure, hot end temperature, reservoir volume and opening of orifice were changed to test the optimum load impedance for the maximum acoustic power by RC (Resistor and Capacitor) load method. To make use of the acoustic power efficiently, a pulse tube refrigerator (PTR) was designed based on this impedance to match the TCP and relative coupling experiments were conducted for the first time. The refrigerating performance of PTR was observed and the lowest no-load temperature of 70.4 K was obtained at its optimum working frequency 5.6 Hz. Also, the performance characteristics and total impedances of three different PTRs were compared to verify the rationality of the impedance matching method in this paper. The calculation results agree well with the substantial experiments and further optimization methods were also proposed.

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1. Introduction

With the energy supply of world is ever growing tense, energy conservation and recycle are increasingly becoming a focus of the research conducted by worldwide scholars [1]. Developing power machinery which can make full use of solar energy, biomass energy and industrial waste heat will greatly improve energy utilization efficiency and reduce electricity consumption [2]. This paper introduces a novel thermocompressor driven pulse tube refrigerator which is based on the principle that gas temperature change will lead to pressure fluctuations and thus the expansion cooling effect will happen in the cold end of PTRs. Compared with traditional refrigerators, it has the advantages of compactness, low vibration and high reliability. The recycle of low-grade heat or waste heat as heat source has a great significance for energy conservation and integrated utilization.

However, most studies on TCPs only concentrated on the working model until now. Few attention were paid to the utilization of their output acoustic power. Peterson [3] studied the engine cycle based on thermocompression, isothermal expansion and isobaric reduction in volume with an external heat source, which led to a high practical efficiency without the increment of dead volume. Kornhauser [4] analyzed the thermal and volumetric efficiency of TCP. It was proved that the thermal efficiency of TCP is higher than that of an ideal Otto engine-driven mechanical compressor. Xue and Wang [5] measured the output pressure ratio of TCPs used as pressure wave generators by comparison of theoretical isothermal model and experimental results. They concluded that large temperature difference can lead to large pressure ratio and the dead volume will deteriorate the performance of TCPs. Wu [6] established the thermodynamic model of TCPs by numerical calculations.

Thus, in order to investigate the utilization of output acoustic power of TCPs, the PTR is chosen as an appropriate load. In recent years, many types of cryocoolers have been developed, including J-T type, Brayton type, Stirling type, G-M type, etc. However, most

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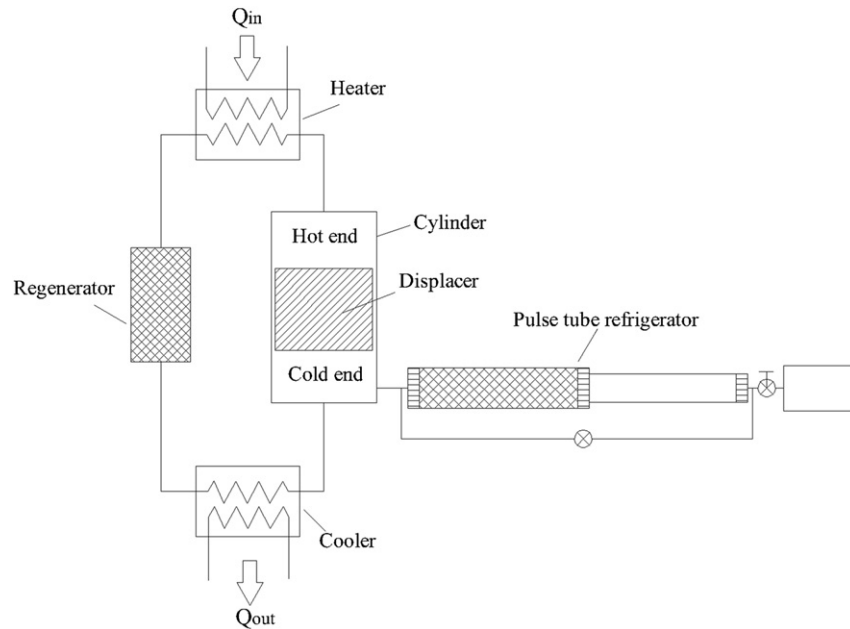


Fig. 1. Schematic of TCP driven PTR.

types are driven by mechanical compressor using electricity while only thermoacoustic engine driven PTR can use waste heat [7,8]. So, this paper has conducted a study on the coupling mechanism of TCP driven PTR by theoretical analysis and experiments.

2. Description of apparatus of TCP driven PTR

2.1. Experimental apparatus

Fig. 1 is the schematic of TCP driven PTR. The displacer is driven by crank link with a frequency of 3–6 Hz. Due to the small pressure difference between the displacer sides, only about 70 W of electrical power is needed to overcome the frictional resistance and flow resistance of the flow passages. The displacer is filled with micro glass balls to reduce the axial heat conduction and weight. Heating rods are used to simulate waste heat to warm up the gas in hot end. In addition, the heater is packed with aluminum silicate as insulation material to reduce heat losses to environment. Gas in the cold end is maintained at room temperature by water chiller. There is a regenerator filled with stainless steel screens between the two ends. It absorbs heat in the hot half cycle and rejects heat in the cold half cycle. Also, thermocouples and pressure transducers are employed in both ends to precisely measure the temperature and pressure. The in-line type PTR designed here is connected to the cold end of TCP with orifice-reservoir and double-inlet as the phase shifter [7]. The phase difference between pressure wave and velocity wave can be adjusted to obtain the optimum performance of refrigerator. All the values of pressure and temperature are collected by computer and analyzed with Labview software.

2.2. Working process

At first, the system is filled with helium gas. When the displacer is in the upper dead point, most of the gas is in the cold end. The gas rejects heat to the water chiller and the system pressure reaches the lowest value as a result of the lowest average system temperature. Then the displacer moves toward to the bottom dead point and the gas is pushed to the hot end through regenerator. The gas absorbs heat from regenerator and hot end heater in this

process. Then the system pressure increases as a result of the increment of the average system temperature. When the displacer reaches the bottom dead point, most of the gas is in the hot end and the system pressure reaches the highest value. Thus, the TCP undergoes a cycle in which the system pressure changes from the lowest value to the highest value. Therefore, a periodic sinusoidal pressure wave is generated and exported to the PTR, and then the cooling effect happens at the cold end by adiabatic expansion process.

However, due to the uncertainty of the volume flow rate from cold end to the regenerator and PTR, the process is an unsteady flow of mass variable problem. Compared to traditional compressor, the phase difference between pressure wave and velocity wave is hard to calculate to determine the coupling load. Thereby, the largest output acoustic power is tested firstly and the corresponding load impedance is calculated to design a coupling PTR in this paper.

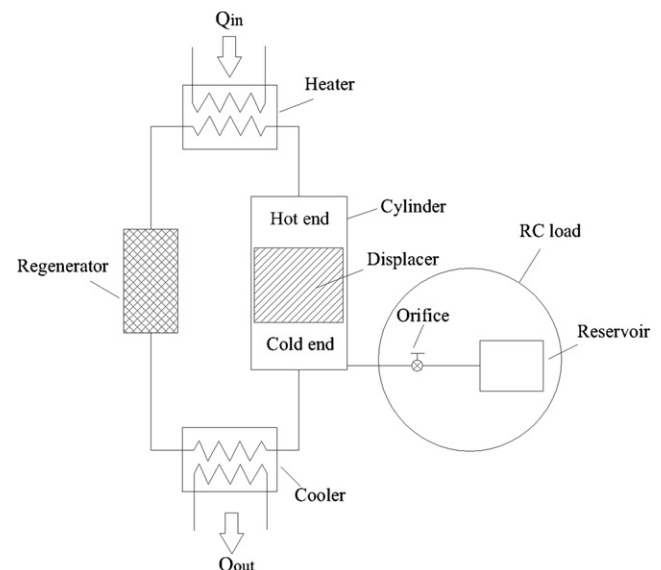


Fig. 2. Schematic of RC load method for acoustic power measurement system.

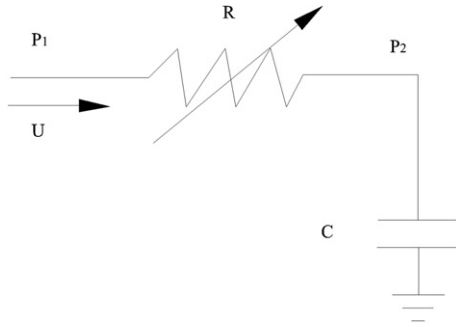


Fig. 3. Equivalent impedance schematic of RC load method.

3. Theoretical and experimental study of acoustic power measurement

3.1. Principle of RC load measurement

Acoustic power represents the average acoustic energy per unit time and area perpendicular to the sound propagation direction. It reflects the capacity of TCP to drive PTR. Therefore, the performance characteristics of PTR can be better understood by accurate measurement of acoustic power and it has a great significance for the design of PTR. Fig. 2 is the schematic of the RC load acoustic power measurement system. Four gas reservoirs with volume of 0.4 L, 0.6 L, 0.8 L and 1.0 L were connected to the cold end of TCP by a needle valve (orifice) respectively. The needle valve was cooled to take away the heat generated by dissipation of acoustic power. The output acoustic power of TCP was tested under the conditions of different reservoirs and opening of orifice. As the size of load is much smaller than the acoustic wavelength, the lumped parameter method can be used here to analyze the experimental result. As shown in Fig. 3, the orifice and reservoir can be regarded as a resistor R and a capacitor C respectively by analogy [9].

Based on classic thermoacoustic theory, the general expression for acoustic power $\dot{E}$ is

$$\dot{E} = \frac{1}{T} \int \hat{P} \cdot \hat{U} dt = \frac{1}{2} \text{Re}(\hat{P} \cdot \hat{U}^*) \quad (1)$$

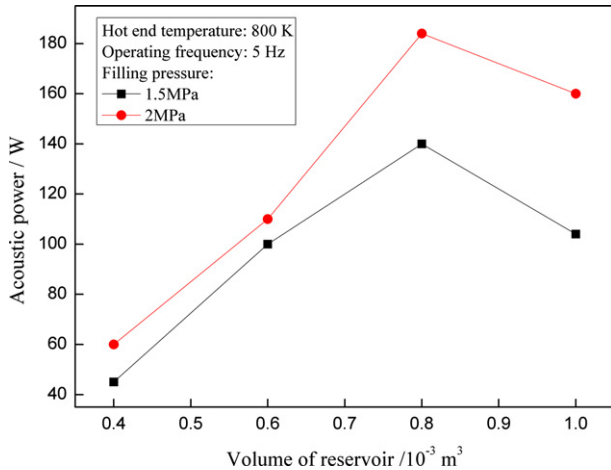


Fig. 4. Variation of acoustic power with the reservoir volume in different filling pressures.

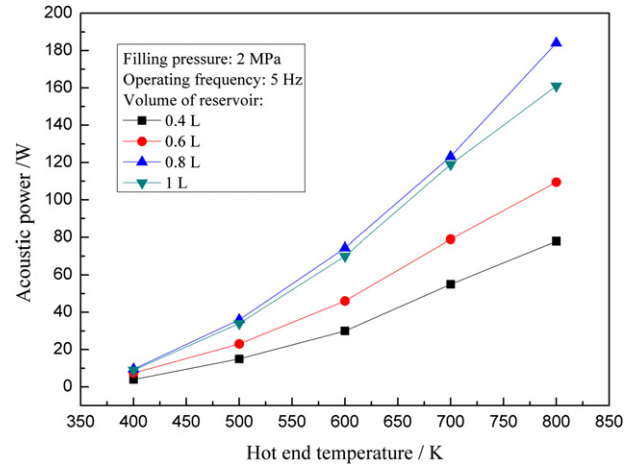


Fig. 5. Variation of acoustic power with the reservoir volume in different hot end temperatures.

where T is the time of a cycle, $\hat{P}$ is complex pressure, $\hat{U}^*$ is conjugate complex volume flow rate.

In this calculation, the complex volume flow rate can be obtained by indirect calculation of capacitance of the reservoir

$$\hat{U} = \hat{P}_2 \cdot i\omega V / \gamma P_0 \quad (2)$$

Thus, the acoustic power can be expressed as

$$\dot{E} = \frac{1}{2} \text{Re}(\hat{P}_1 \cdot \hat{U}^*) = \frac{1}{2} \omega V |\hat{P}_1| \cdot |\hat{P}_2| \cdot |\sin \theta| / \gamma P_0 \quad (3)$$

where $\hat{P}_1$ is complex pressure before the orifice, $\hat{P}_2$ is complex pressure after the orifice, P_0 is the initial filling pressure of TCP, V is volume of the reservoir, ω is angular frequency of the output pressure wave, θ is the phase difference between $\hat{P}_1$ and $\hat{P}_2$, γ is the specific heat ratio.

The parameters ω , γ , V and P_0 in Equation (3) are known values. $\hat{P}_1$, $\hat{P}_2$ and θ can be measured by pressure transducers.

3.2. Experimental results and discussion

The output acoustic power of TCP was measured under different reservoirs, opening of orifice, hot end temperature and filling

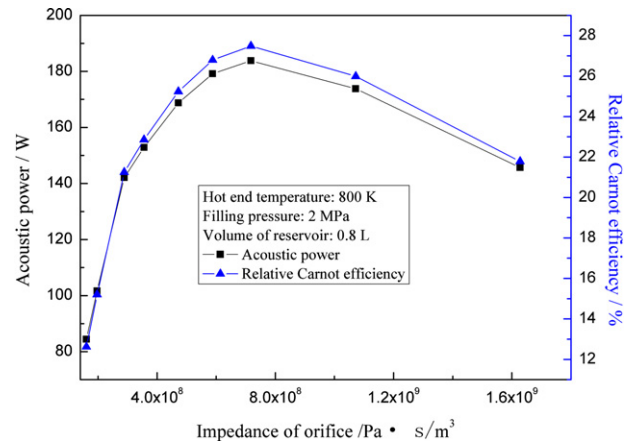


Fig. 6. Variation of acoustic power and relative Carnot cycle efficiency with the orifice impedance.

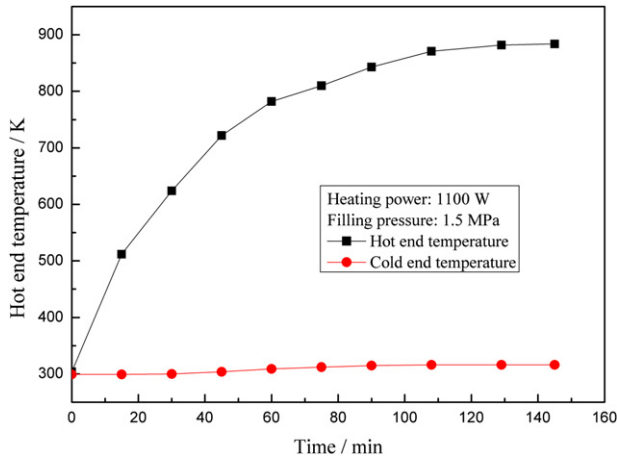


Fig. 7. Variation of hot and cold end temperature with time.

pressure. Fig. 4 shows the variations of acoustic power with the volume of reservoirs under different filling pressures when the heating power is 1070 W at 800 K. All the values are measured under the optimum opening of orifice. The acoustic power increases firstly and then decreases with the increment of volume of reservoirs. When the volume of reservoir is 0.8 L, the maximal acoustic power can be 184 W at 2 MPa and 140 W at 1.5 MPa. Thus we can conclude that the imaginary part of load impedance has a great effect on acoustic power.

Fig. 5 shows the variations of acoustic power with the hot end temperature under different volumes of reservoirs when the filling pressure is 2 MPa at 5 Hz. The acoustic power gradually increases with the increment of hot temperature and has an optimum volume of 0.8 L.

Fig. 6 shows that the acoustic power and relative Carnot efficiency varies with the opening of orifice when the filling pressure is 2 MPa at 800 K. When the opening of orifice decreases, the real part of load impedance i.e. the impedance of orifice increases. Both the acoustic power and relative Carnot efficiency increase firstly and then decrease with the increment of impedance of orifice. As the impedance of orifice reaches 7×10^8 Pa s/m³, the maximum acoustic power is 184 W with a relative Carnot efficiency of 27.5%. According to the optimum load impedance measured above, we can design a coupling PTR for the TCP [10].

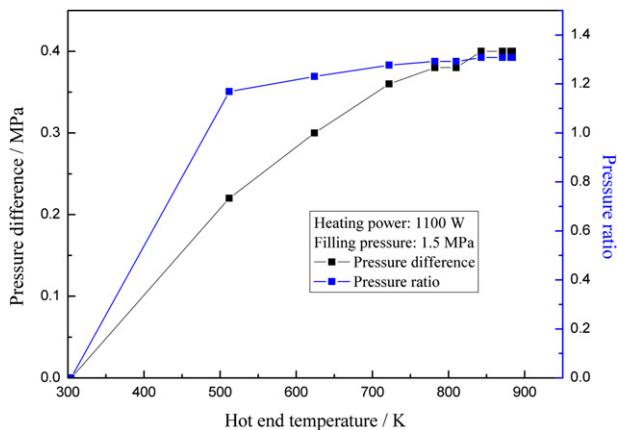


Fig. 8. Variation of pressure difference and ratio with heating temperature.

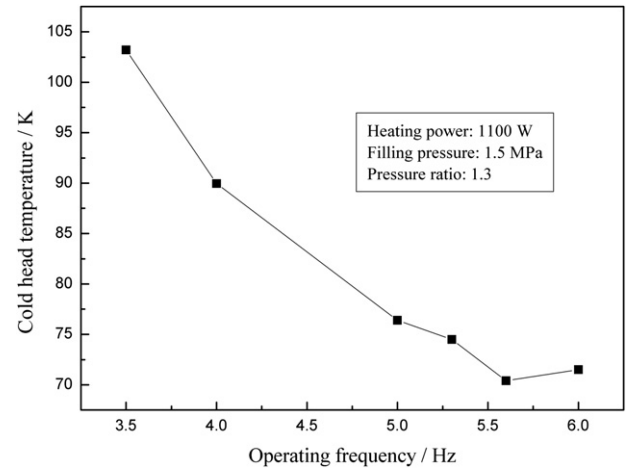


Fig. 9. Variation of cold head temperature with frequency.

4. Design and experimental study of PTR

4.1. Theoretical design of coupling PTR

According to the measurement result of acoustic power, we have obtained the optimum load which includes a 0.8 L reservoir and an orifice with impedance of 7×10^8 Pa s/m³. The capacitance of gas reservoir can be calculated by Equations (4) and (5), which is $-1.3 \times 10^8 i$. Therefore we finally get the optimum load impedance of $(7-1.3i) \times 10^8$ Pa s/m³ for this TCP.

$$C = V/\gamma P_0 \quad (4)$$

$$Z = 1/i\omega C \quad (5)$$

where C is acoustic capacitance of the reservoir, Z is impedance of the reservoir.

Referring to reference [10], we can design a single-stage PTR with total impedance equal to the optimum load impedance by numerical simulation. The impedances of regenerator and pulse tube are calculated by thermoacoustic theory respectively [11]. Also, orifice-reservoir and double-inlet are employed as the phase shifter to adjust the total impedance of PTR in a certain range.

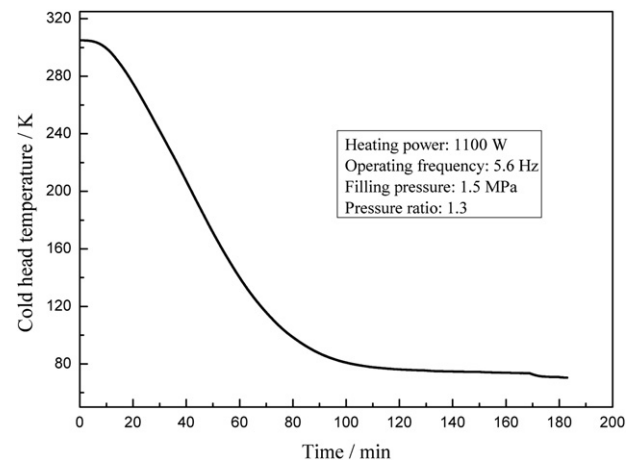


Fig. 10. Typical cooling curve of TCP driven PTR.

Table 1

Dimensions and lowest no-load temperature of the three PTRs.

	Regenerator (Diameter × Length) (mm)	Mesh of screens	Pulse tube (Diameter × Length) (mm)	Impedance $10^8 \times (\text{Pa} \cdot \text{s}/\text{m}^3)$	Lowest cooling temperature (K)
PTR I	18 × 150	1/3 150 + 2/3 120	11.2 × 150	4.5–1.6i	70.4
PTR II	30.2 × 108	250	18 × 144	1.1–0.64i	114
PTR III	23.2 × 51 + 17.4 × 28	400	11.3 × 105	1.5–0.36i	120

4.2. Experimental results and discussions

Compared to traditional compressors, the initial pressure wave of TCP is not stable but gradually established based on the temperature difference between hot and cold ends. A good heat exchange system has a great impact on the efficiency of this refrigerator. Fig. 7 is the heating process of TCP. With a heating power of 1100 W, the hot end temperature kept increasing and maintained a thermal equilibrium with the environment at 880 K. The cold end temperature was kept at around 310 K under the cooling of water chiller.

As shown in Fig. 8, when the hot end temperature gradually increased, the temperature difference between hot and cold ends increased, too. Meanwhile, the pressure difference and pressure ratio became more and more large and finally maintained at 0.4 MPa and 1.3.

The low-frequency PTR is sensitive to frequency because its impedance will be changed with different frequencies. In this experiment, the lowest no-load temperature was tested around frequency 3 ~ 6 Hz. As shown in Fig. 9, the cold head temperature of PTR decreased gradually when frequency increased. The lowest no-load temperature is 70.4 K at 5.6 Hz with 1 W cooling capacity at 85 K. Since then the cold head temperature continued to increase until the frequency reached 6 Hz. Thereby 5.6 Hz can be chosen as the best coupling frequency for this TCP driven PTR.

Fig. 10 is the typical cooling curve of the refrigerator at 5.6 Hz. Compared with traditional Stirling type PTR, the cooling process is slower for the pressure ratio is gradually established with the increment of hot end temperature and a lower operating frequency. Figs. 7 and 8 show that the pressure ratio will reach 1.2 when the hot end temperature is 500 K after 20 min heating. Then the refrigerator had a rapid cooling rate until the liquid nitrogen temperature was achieved.

Compared with thermoacoustically driven PTR, the efficiency of TCP driven PTR is a little lower [12–14]. After years of research and development, the recent report showed that the thermoacoustically driven PTR have obtained a lowest no-load temperature of 18.7 K. However, it needs a larger heating power of 2700 W and a higher filling pressure of 2.7 MPa. Also, a long resonator tube of 1.6 m, an acoustic amplifier and a two-stage PTR was employed. This will increase the complexity and size of the refrigerator [15]. Thus, the research of TCP driven PTR has a great significance for cryogenic refrigerators.

4.3. Comparison of three different PTRs

In order to verify the reasonability of the impedance match method, we have manufactured another two different PTRs connected to the TCP to test their refrigerating characteristics. All the impedances of three PTRs were calculated according to the numerical simulation method in Ref. [11]. The dimensions and lowest temperatures of the three PTRs are listed in Table 1 among which PTR I is the one designed in Section 4.1.

In Table 1, PTR I and PTR II are in-line type while PTR III is coaxial type. The optimum load impedance obtained in Section 4.1 is $(7-1.3i) \times 10^8 \text{ Pa} \cdot \text{s}/\text{m}^3$. As shown in Table 1, the impedance of PTR I is closest to the optimum value and the refrigerating temperature is also the lowest one. Considering to obtain the lowest temperature, the actual operating pressure and frequency is a little different from the optimum working condition of TCP. Therefore the impedance of

PTR I is not exactly the optimum load impedance calculated in Section 4.1. However, compared with PTR I, the refrigeration characteristics of PTR II and PTR III with the impedances severely deviating from the optimum value are poorer. Their lowest temperatures are nearly 50 K higher than that of PTR I. Therefore it can be verified the impedance match method is a good way to provide basis for the coupling study of TCP driven PTR.

5. Conclusion

The theoretical and experimental methods are applied to study the performance characteristic of TCP. Through RC load method, the maximum acoustic power can reach 184 W with a relative Carnot efficiency of 27.5%. Meanwhile, the optimum load impedance was obtained. Then the coupling PTR was designed based on this impedance. The lowest temperature of 70.4 K and 1 W at 85 K can be achieved when the heating power is 1100 W. It's the first time that TCP is used in cryogenic field and the TCP driven PTR have broken through the liquid nitrogen temperature.

Through increasing the filling pressure, improving the efficiency of heat exchangers, optimizing the parameters of regenerator and more in-depth study of the coupling mechanism of the TCP driven PTR, its refrigerating characteristic will be further improved.

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